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GROUND FACILITIES FOR TESTING REENTRY STRUCTURES AND MATERIALS

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Introduction

Successful development of re-entry vehicles is vitally dependent upon materials and structures that have been thoroughly tested in ground facilities which simulate or reproduce the important characteristics of the re-entry environment. Various approaches for providing the required test conditions in the laboratory are considered herein, with emphasis on the facility design approaches used at the NASA Langley Research Center. Problems encountered in the design of these facilities are discussed and facility utilization is illustrated by brief descriptions of typical research projects. A somewhat similar review is given in reference 1, which lists 32 other publications on test facilities; references listed herein were published after reference 1.

HEATING EXPERIENCE

Intense heat is the re-entry environmental factor most important in structural design. The magnitude of the heating rates, heat loads and temperatures encountered by the vehicle along with the relative variation of enthalpy, heat rate and dynamic pressure during reentry must be considered to establish facility design specifications. The heating experiences of current and projected re-entry vehicles presents a tremendous challenge to the facility designer. (Refs. 2-3, Figs. 1-4)

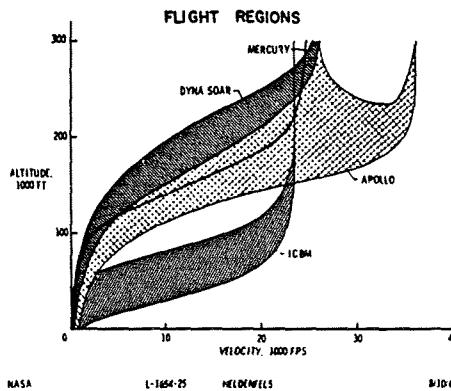


Fig. 1—Flight Regions.

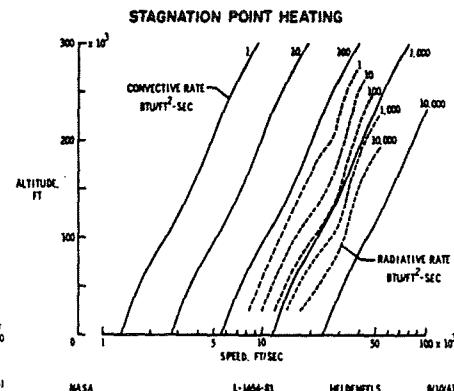


Fig. 2—Stagnation Point Heating.

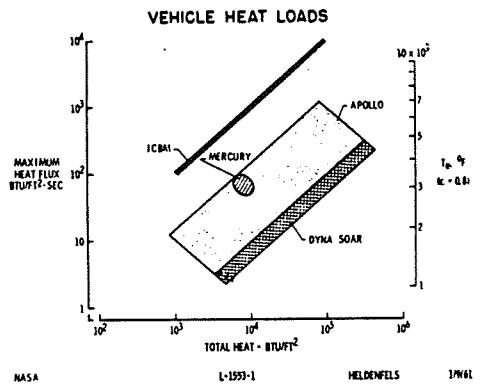


Fig. 3—Vehicle Heat Loads.

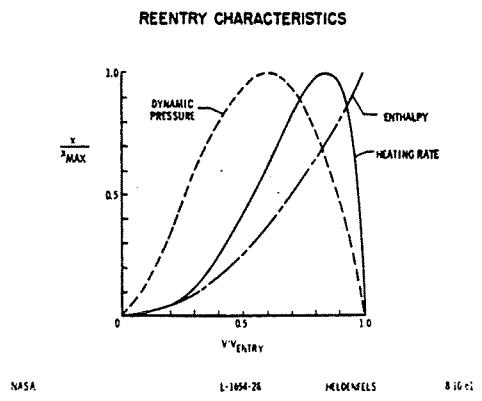


Fig. 4—Reentry Characteristics.

SIMILARITY PARAMETERS

Similarity parameters that govern the scaling of aerodynamically heated structural models require the testing of full-scale structures for complete similarity because of the many different physical phenomena involved. Scale-model tests are feasible for restricted purpose investigations wherein certain conditions are relaxed. The details of the structure and the heat protection systems, however, usually cannot be reproduced adequately in small-scale models, so that full-scale testing of materials and structural components is needed. The similarity or scaling problem is of greater significance in tests involving aerothermoelastic effects which can be important at supersonic or hypersonic speeds during either atmospheric exit or entry. (Refs. 4-6, Fig. 5)

SIMILARITY PARAMETERS

STRESSES AND DEFLECTIONS

$$\epsilon \propto \frac{g}{E} \frac{G}{E} \frac{x}{L} \frac{\theta}{L} \propto \sigma_s T, \frac{P}{E L^2} \frac{\rho L^2}{E L^2}, \frac{\rho g L}{E}$$

TEMPERATURE DISTRIBUTION

$$\frac{T}{T_0} \propto \frac{k t}{c \rho L^2} \frac{\eta L}{k}, \epsilon \frac{\sigma_s L T^3}{k}, \frac{\rho g L}{k T}$$

AERODYNAMICS

$$\frac{P}{\rho V^2} \propto \frac{x}{L} \propto \frac{V}{a} \frac{\rho V L}{\mu}, \frac{T}{T_0} \frac{\eta L}{k} \frac{C_p}{k} \frac{C_t}{V^2} \frac{V_t}{L}$$

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Fig. 5—Similarity Parameters.

EQUIPMENT TYPES

The various types of equipment which produce sufficient heating for re-entry testing are listed in Fig. 6. Each has advantages and disadvantages that determine its range of usefulness. (Ref. 1)

HEATING EQUIPMENT TYPES

<u>AERODYNAMIC HEATING</u>	<u>NONCONVECTIVE HEATING</u>
WIND TUNNELS AND JETS HEAT EXCHANGERS DIRECT COMPRESSION COMBUSTION ELECTRIC ARCS SHOCK TUBES AND TUNNELS GUN-LAUNCHED PROJECTILES ROCKET PROPELLED MODELS	INCANDESCENT ELEMENTS INDUCTION COILS ELECTRIC BLANKETS ELECTRICAL RESISTANCE IMAGING FURNACES SOLAR ELECTRIC ARC

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Fig. 6—Heating Equipment Types.

FURNACES AND RADIATORS

For tests in which heating is a primary consideration and the way in which this is done is unimportant, various forms of ovens, furnaces and radiant heating devices can be used to test structures and materials. Test facilities in this category account for most of the high-temperature laboratory apparatus now in use.

Conventional Furnaces

Ovens and furnaces can be used to test materials specimens and structural components and assemblies at elevated temperatures for long times to de-

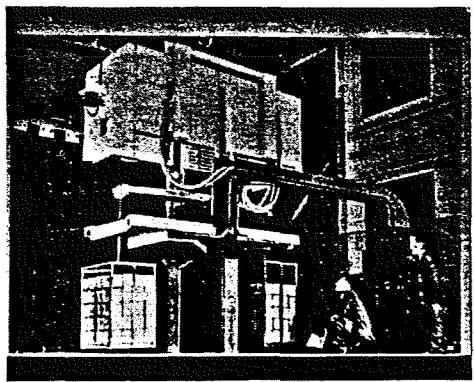


Fig. 7—Creep Test Equipment.



Fig. 8—Induction Heating Apparatus.

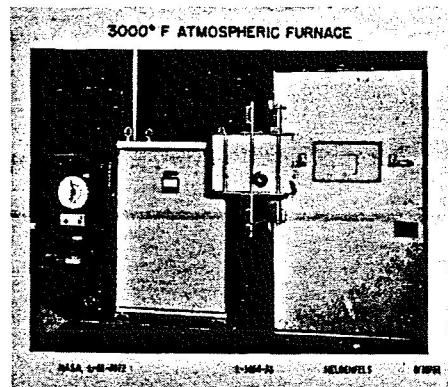


Fig. 9—3000° F Atmospheric Furnace.

determine the effects of material deterioration and creep on the strength, deformation and other characteristics of interest. (Figs. 7-9)

Radiant Heating Devices

Carbon rods, glow bars and various forms of lamps have been used to produce the time variations of temperature experienced in reentry. Quartz-tube heat lamps have proven to be the most satisfactory. These lamps are available in several lengths and sizes and can be assembled in various arrays to produce heating rates up to about 200 Btu per square foot per second on the test specimen. Components can be assembled for specific purposes and complete systems are commercially available. Quartz-lamp heating equipment is used in testing laboratories throughout the world. For short time applications, no cooling of the lamps or their holders is required, but for prolonged use at high temperature, both air and water cooling systems have been successfully used. (Ref. 7, Figs. 10-13)

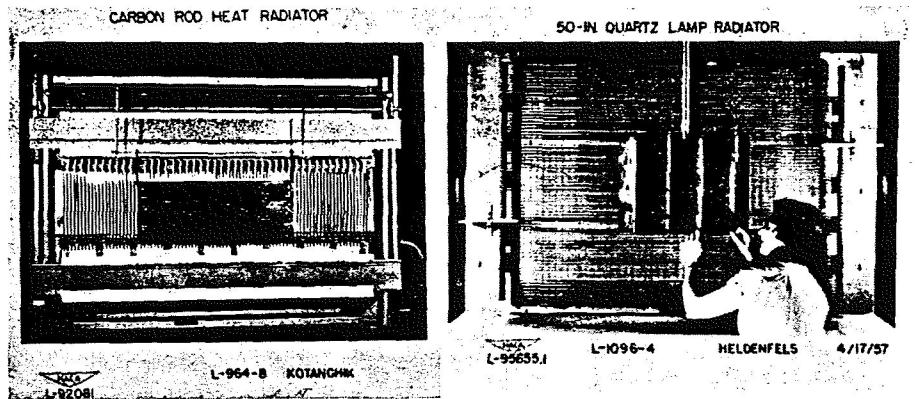
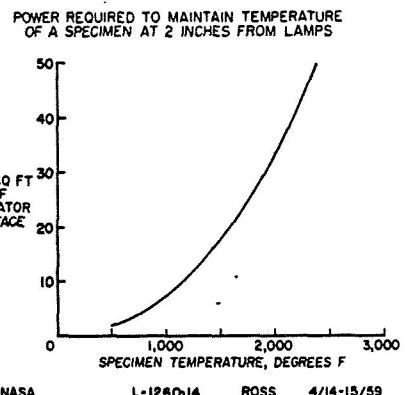
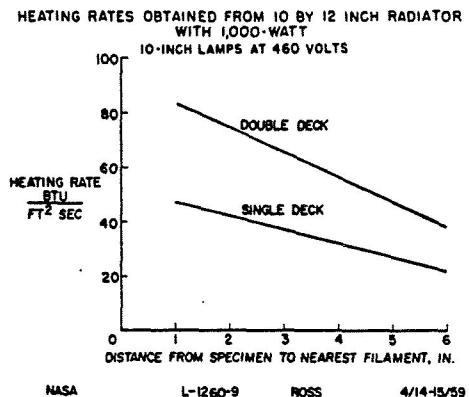


Fig. 10—Carbon Rod Heat Radiator.

Fig. 11—50-in. Quartz Lamp Radiator.



(Left) Fig. 12—Heating Rates Obtained From 10 by 12 inch Radiator with 1,000 Watt 10-inch Lamp at 460 Volts.

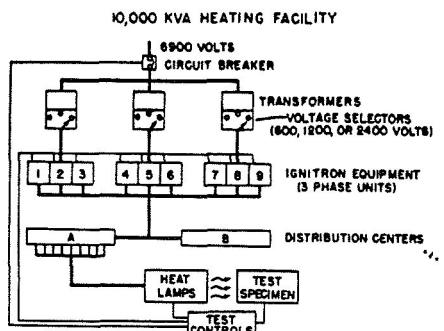
(Right) Fig. 13—Power Required to Maintain Temperature of a Specimen at 2 inches from Lamps.

Power Supplies and Controllers

Application of the quartz-tube heat lamp to structural testing requires a suitable power supply and controller to regulate the voltage to the lamps so that the test specimen receives the desired variation of heat input. Either of three control modes can be used. Large installations for testing complete structures have many channels of power control for adequate simulation of the heat distribution over the surface of the structure. (Figs. 14-15)

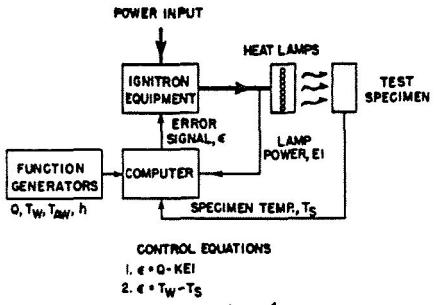
Applications of Quartz-Lamp Heaters

The quartz-tube heat lamp is a versatile unit that has been arranged in many different ways to test structures and materials. (Refs. 1, 8-9, Figs. 16-23)



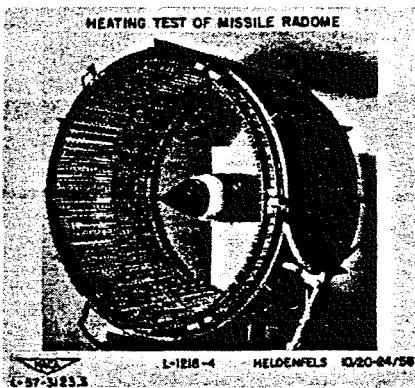
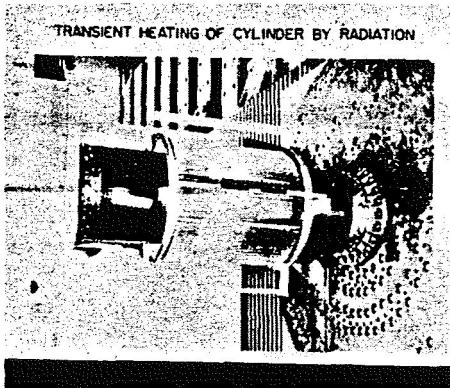
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HEATING FACILITY CONTROL SYSTEM

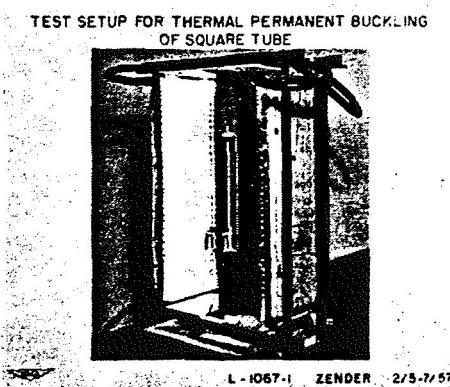


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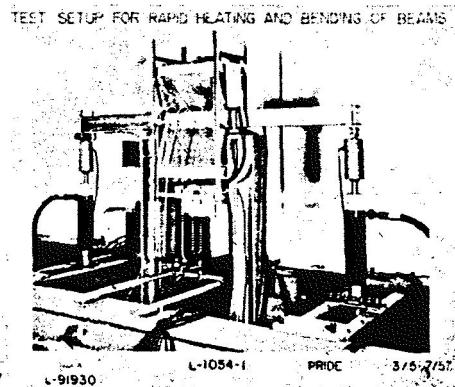
(Left) Fig. 14—10,000 KVA Heating Facility.
(Right) Fig. 15—Heating Facility Control System.



(Left) Fig. 16—Transient Heating of Cylinder by Radiation.
(Right) Fig. 17—Heating Test of Missile Radome.

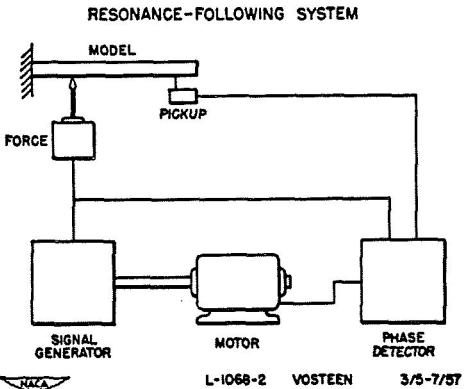
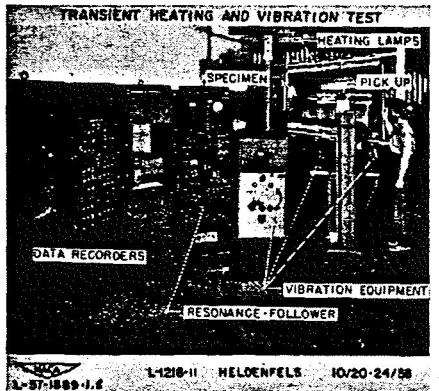


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(Left) Fig. 18—Test Setup for Thermal Permanent Buckling of Square Tube.
(Right) Fig. 19—Test Setup for Rapid Heating and Bending of Beams.



(Left) Fig. 20—Transient Heating and Vibration Test.
 (Right) Fig. 21—Resonance-Following System.

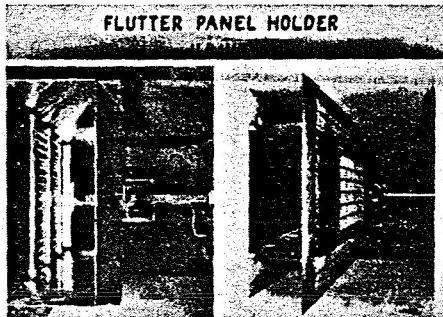
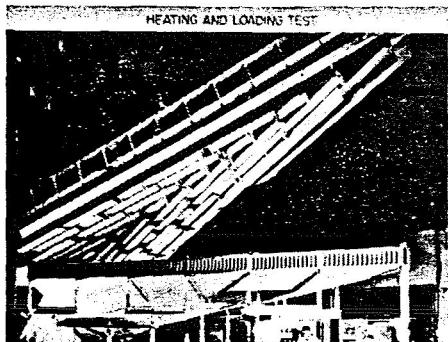
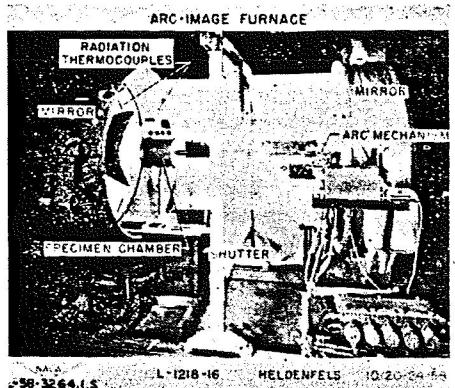


Fig. 23—Flutter Panel Holder—U.P.W.T.

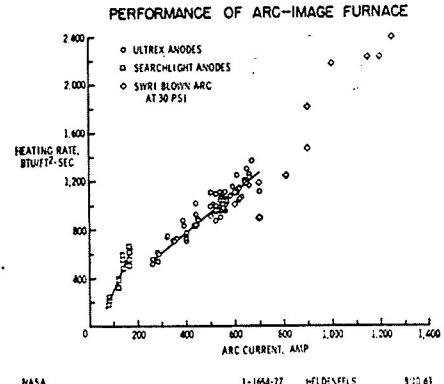
Fig. 22—Heating and Loading Test.

Arc-Image Furnaces

To obtain heating rates higher than available from solid, incandescent, radiating elements, high-intensity sources of radiant energy are used in solar and electric-arc furnaces. These devices direct the image of the source onto a test specimen by means of mirrors and provide pure radiant heating of high intensity and long duration. Arc-image furnaces are preferred for laboratory use; custom built devices are used in many laboratories but some designs are commercially available. (Ref. 10, Figs. 24-25)



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(Left) Fig. 24—Arc-Image Furnace.

(Right) Fig. 25—Performance of Arc-Image Furnace.

AERODYNAMIC HEATING

Type of Facilities

The dynamic effect of air flow on the integrity of materials and structures can be an important consideration, thus tests in which the specimen is both heated and loaded aerodynamically are required. Figure 26 lists wind tunnels and jets at the NASA Langley Research Center used to test structures and materials under conditions that simulated or exactly duplicated

LANGLEY WIND TUNNELS AND JETS FOR STRUCTURES AND MATERIALS TESTING			
NAME	MACH NUMBER	ENTHALPY, BTU/LB	TEST SECTION SIZE, IN.
9- BY 6-FT THERMAL STRUCTURES TUNNEL	3	285	72 x 105
HOT CORE MODIFICATION	• 3	760	72 x 105
MODEL TUNNEL	3	130	6 x 9
8-FT HIGH-TEMP. STRUCTURES TUNNEL	• 7	1400	96
PILOT TUNNEL	7	1140	7
ROCKET MATERIALS JET	• 3	2765	3
CERAMIC-HEATED M = 2 JET	2	1100	0.8
11-INCH TUNNEL	4	1100	4
12-INCH HYPERSONIC	6	1100	11
ARC-HEATED 700 KW LOW PRESSURE SUBSONIC	2	3400	0.5
SUPersonic	0.2	4000	6
1500 KW GRAPHITE	0.02	4500	6
2500 KW COPPER	0.2	3500	4
DC TUNNEL	• 9	3350	20
10 MEGAWATT	• 7	8000	6
	• 9	8000	13
		8000	24

*UNDER CONSTRUCTION

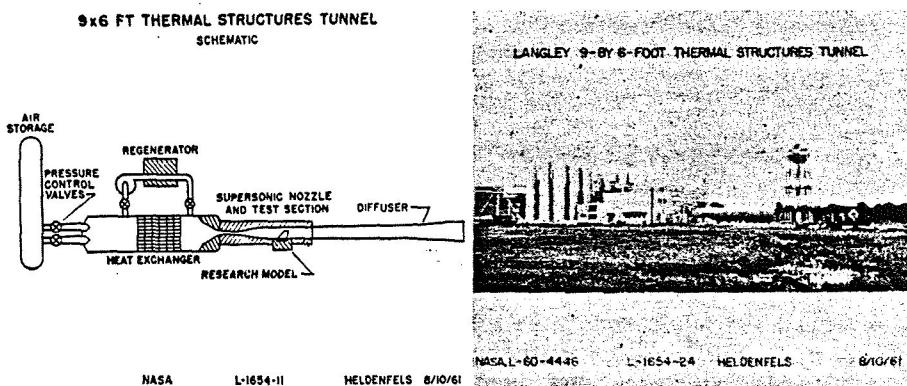
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Fig. 26—Langley Wind Tunnels and Jets for Structures and Materials Testing.

high speed flight. Because each facility is inherently limited to a small part of the flight range or a particular combination of characteristics, a number of facilities are needed.

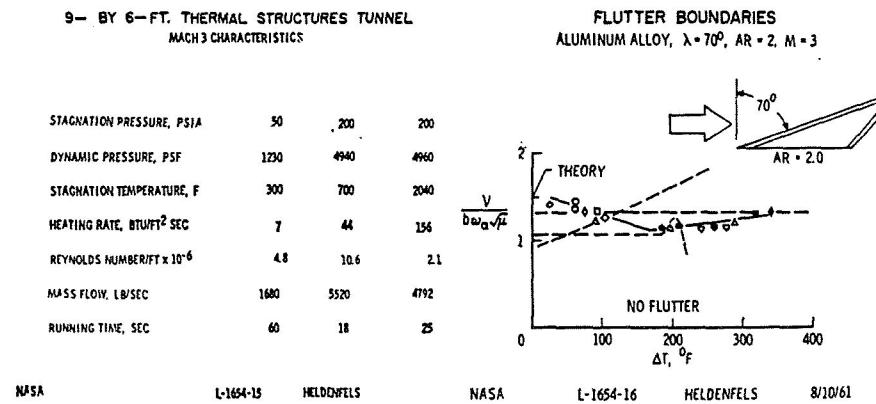
9- By 6-Foot Thermal Structures Tunnel

This is a large supersonic blowdown type wind tunnel that exactly duplicates the conditions encountered in flight at Mach No. 3 in the stratosphere. It was built primarily for investigations of aerothermoelastic problems of supersonic aircraft and missile structures, but re-entry vehicles must pass through this speed range during both exit and entry and may encounter the most severe aerothermoelastic design conditions therein. The problems encountered in the design, operation and utilization of this facility are similar to those of other large aerodynamic facilities that may be built to simulate reentry. The maximum temperature (700° F) will soon be increased to 2040° F by burning natural gas in the settling chamber. (Figs. 27-33)



(Left) Fig. 27—9 x 6 Ft. Thermal Structures Tunnel—Schematic.

(Right) Fig. 28—Langley 9- By 6-Foot Thermal Structures Tunnel.



(Left) Fig. 29—9- by 6-Ft. Thermal Structures Tunnel—Mach 3 characteristics.

(Right) Fig. 30—Flutter Boundaries—Aluminum Alloy, $\lambda = 70^{\circ}$, AR = 2, M = 3.

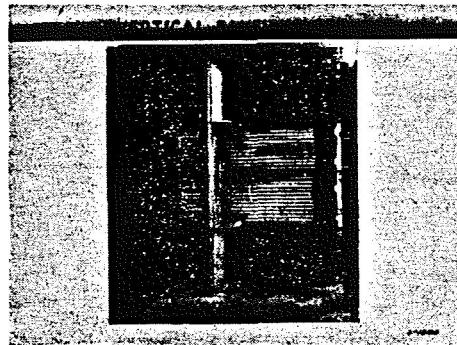
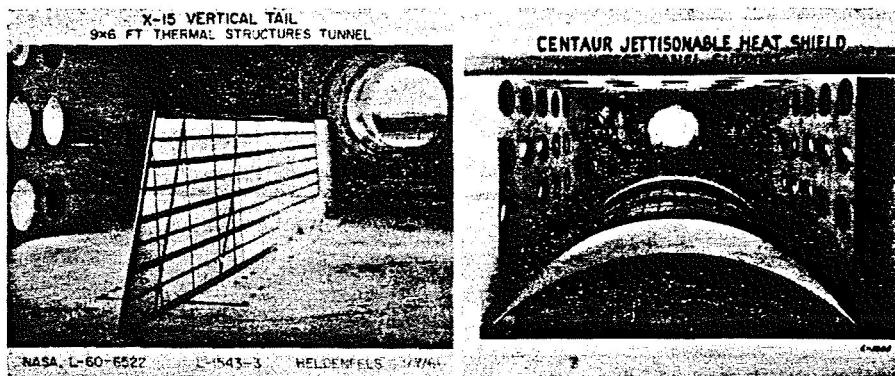


Fig. 31—Vertical Panel Holder.



(Left) Fig. 32—X-15 Vertical Tail—9 x 6 Ft. Thermal Structures Tunnel.

(Right) Fig. 33—Centaur Jettisonable Heat Shield Test Panel Support.

Ceramic Heated Air Jets

A ceramic pebble-bed heater can be used to provide air temperatures much higher than obtainable with metallic heat-exchangers like that used in the 9 x 6 TST. Air at 4000° F is routinely provided by facilities of this type but problems are encountered with the cyclic instability of ceramics suitable for use at high temperatures. (Figs. 34-36)

8-Foot High Temperature Structures Tunnel

Combustion products have been selected as the most practical test medium for a large, high-temperature, hypersonic structures tunnel now under construction at Langley. A pilot model has been used to solve the design and operational problems encountered with this facility. (Figs. 37-44)

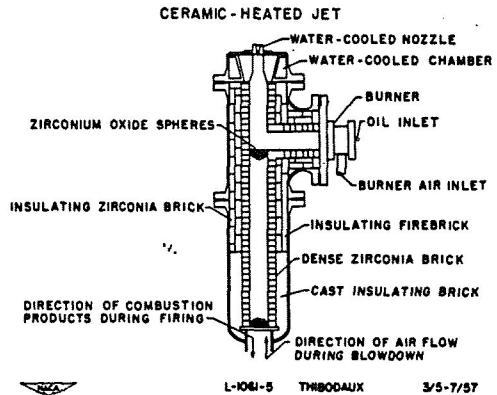


Fig. 34—Ceramic-Heated Jet.

PROPERTIES OF REFRactory OXIDES

MATERIAL	MELTING POINT	USE TEMP.	THERMAL SHOCK	LOAD CAPACITY	LOW TEMP. REACTION	CYCLING STABILITY
STABILIZED ZIRCONIA ZrO_2	4900° F ↓ 4600° F	4500° F	GOOD ↓ POOR	40 PSI AT 3500° F 4 PSI AT 4000° F	MgO Al_2O_3 ThO_2	POOR ↓ GOOD - ?
ALUMINA Al_2O_3	3600° F	3500° F ↓ 3200° F	GOOD		ZrO_2	STABLE
MAGNEStIA MgO	5000° F ↓ 4700° F	3500° F ↓ 3000° F	FAIR		ZrO_2	STABLE
THORIA ThO_2	5800° F ↓ 5500° F	4900° F	POOR	8 PSI AT 4200° F	ZrO_2	STABLE

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Fig. 35—Properties of Refractory Oxides.

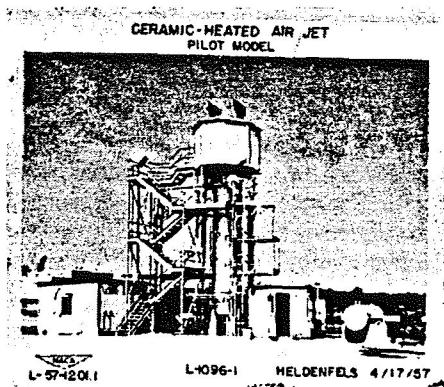
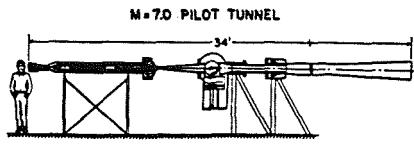
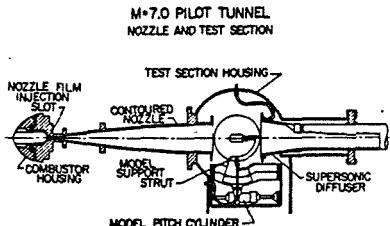


Fig. 36—Ceramic-Heated Air Jet—Pilot Model.



M=7.0
P_{STAG} = 400 TO 2300 PSI
T_{STAG} = 2200 °F TO 3200 °F
DYNAMIC PRESSURE = 300 PSF TO 1200 PSF
RUNNING TIME = 30 SEC TO 180 SEC
TEST SECTION DIAMETER = 7.5 INCHES

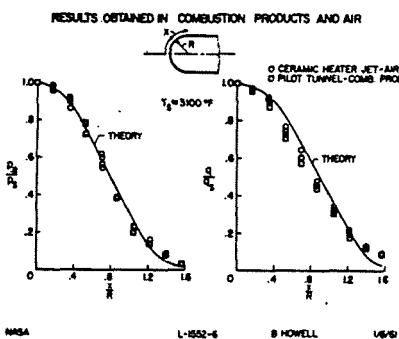
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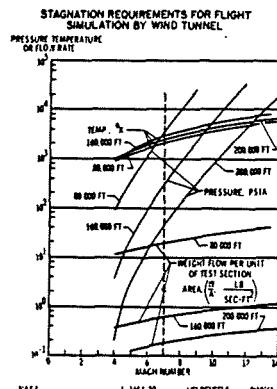
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(Left) Fig. 37—M = 7.0 Pilot Tunnel.

(Right) Fig. 38—M = 7.0 Pilot Tunnel—Nozzle and Test Section.



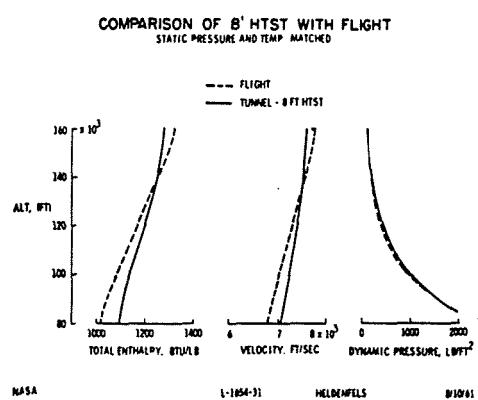
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(Left) Fig. 39—Results Obtained in Combustion Products and Air.

(Right) Fig. 40—Stagnation Requirements for Flight Simulation by Wind Tunnel.



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Fig. 41—Comparison of 8' HTST with Flight—Static Pressure and Temp. Matched.

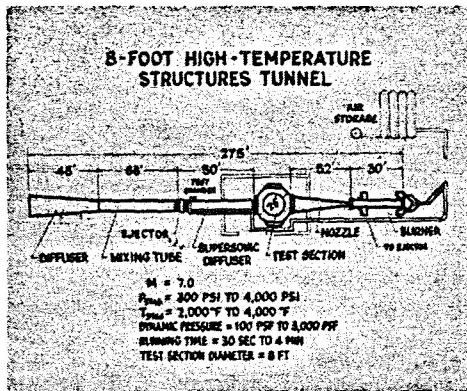


Fig. 42—8-Foot High-Temperature Structures Tunnel.

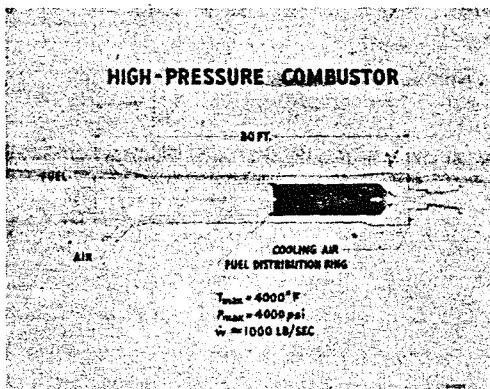


Fig. 43—High-Pressure Combustor.

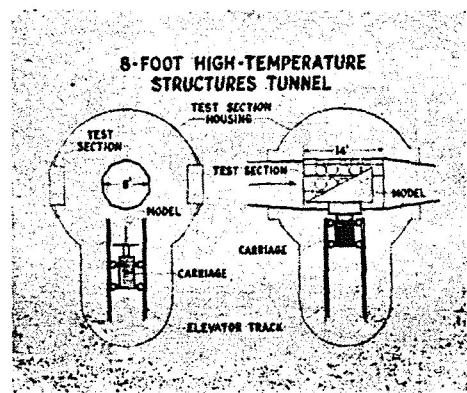


Fig. 44—8-Foot High-Temperature Structures Tunnel—Test Section.

Arc-Heated Jets and Tunnels

The use of electric arcs to heat air to extremely high temperatures provides the most promising approach for simulating the maximum heating conditions encountered during atmospheric entry. Numerous types of arc heaters are under active development, with more than 30 organizations working on them. Several configurations have been developed at Langley, with most of the work directed toward alternating-current arcs because large amounts of power are more readily available with alternating than with direct current. Large facilities are required for adequate testing of structures and materials. Several kinds of arc heaters are described in References 11 through 13 and illustrated in Figures 45 through 57. The

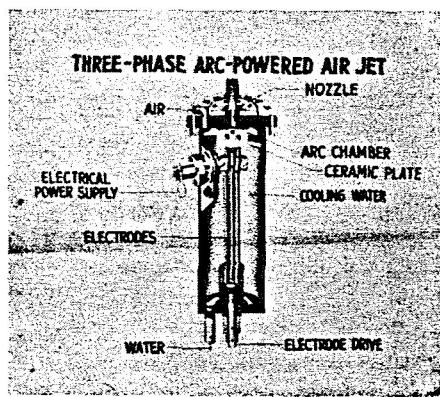
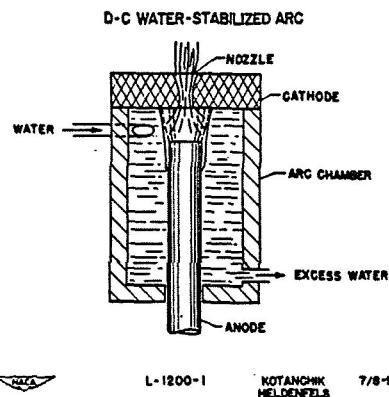


Fig. 45—D. C. Water-Stabilized Arc. Fig. 46—Three-Phase Arc-Powered Air Jet.

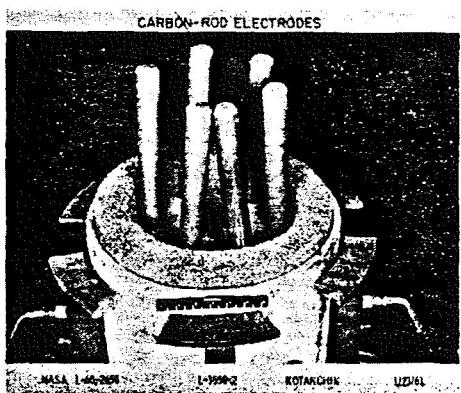


Fig. 47—Carbon-Rod Electrodes.

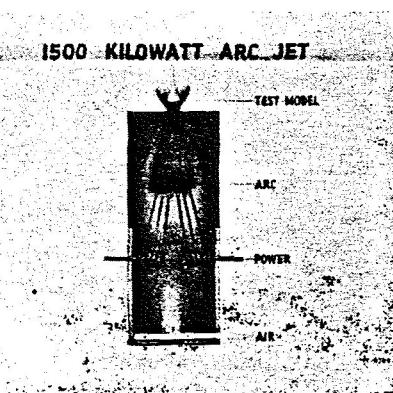


Fig. 48—1500 Kilowatt Arc Jet.

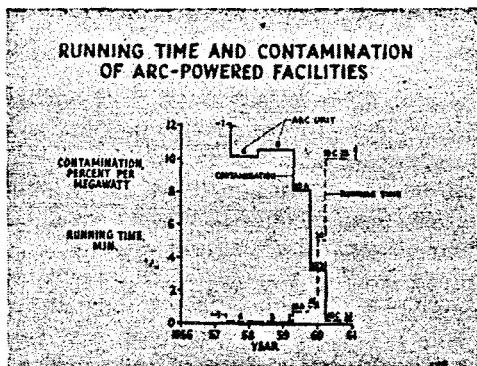
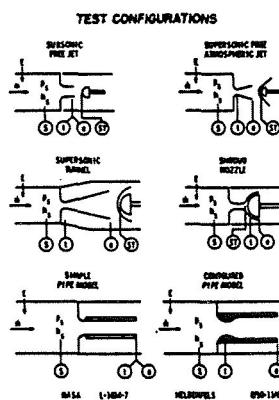
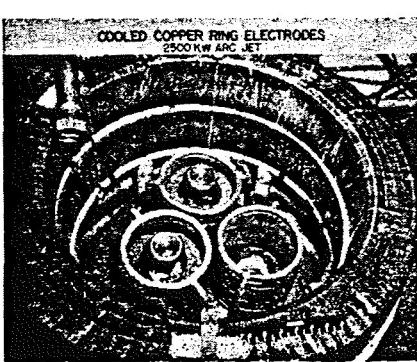
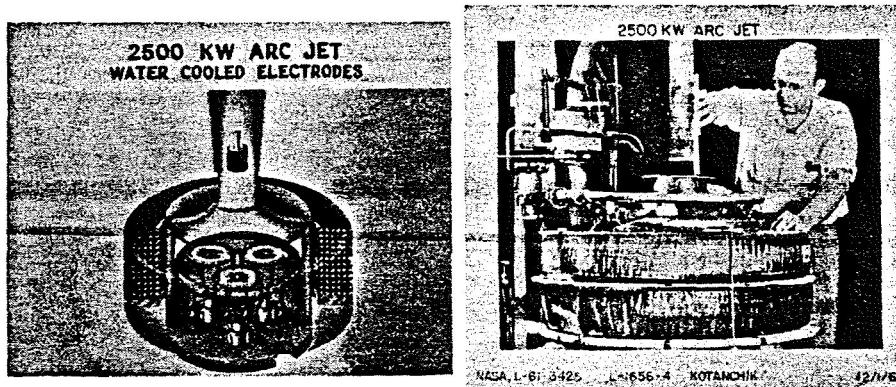


Fig. 49—Running Time and Contamination of Arc-Powered Facilities.



(Left) Fig. 52—Cooled Copper Ring Electrodes—2500 KW Arc Jet.
 (Right) Fig. 53—Test Configurations.

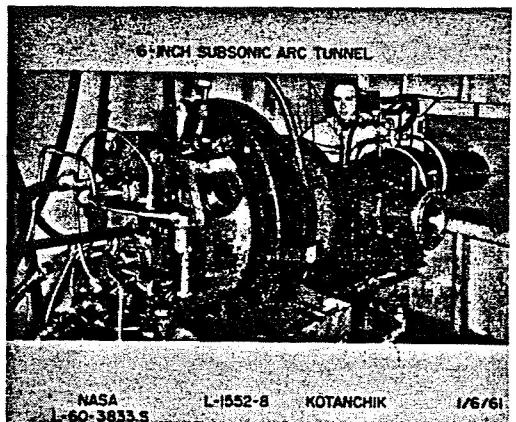


Fig. 54—6-inch Subsonic Arc Tunnel.

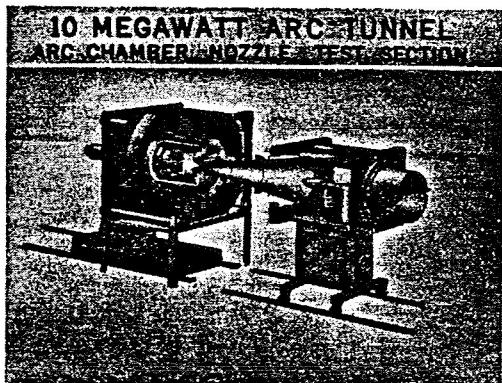


Fig. 55—10 Megawatt Arc Tunnel—Arc Chamber, Nozzle, Test Section.

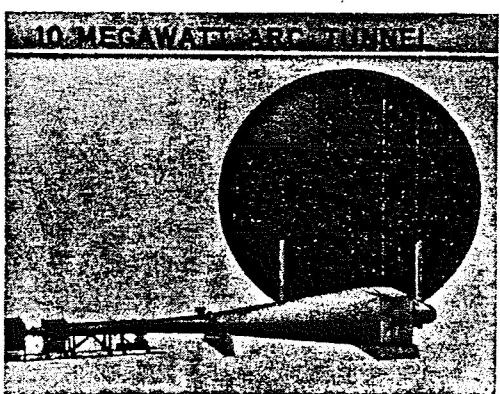
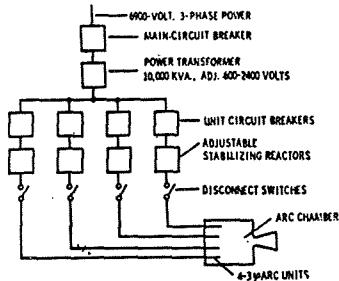


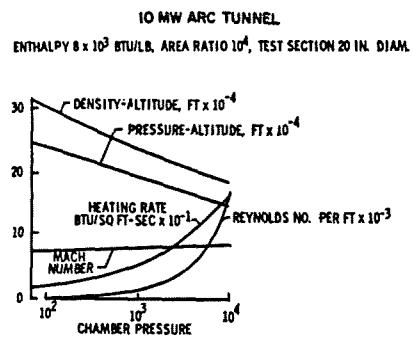
Fig. 56—10 Megawatt Arc Tunnel.



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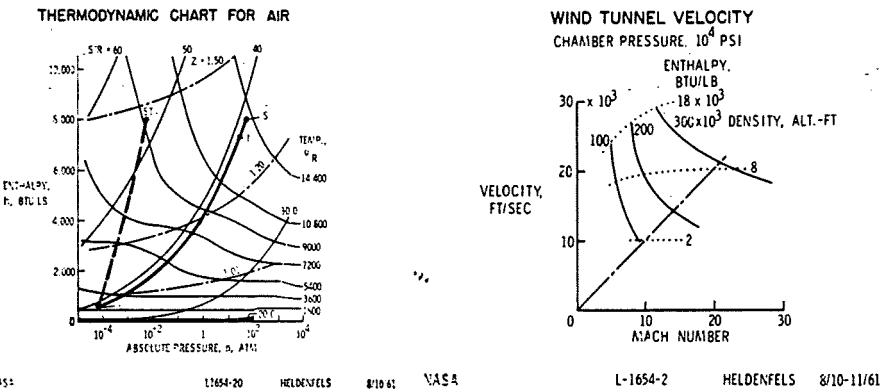
Fig. 57—A. C. Arc-Jet Power Supply.

real-gas properties of high-temperature air substantially influence the capabilities and potentialities of arc-heated wind tunnels; calculations indicate that practical limitations on the pressure and area ratios obtainable will prevent the construction of facilities that exactly duplicate very high speed flight. (Refs. 14-15, Figs. 58-66) An important characteristic of facilities that simulate re-entry heating is the enthalpy (or temperature) of the gas stream; some of the methods used for enthalpy determination are given in Ref. 16 and Figs. 67 through 70. Applications of arc-heated facilities to testing thermal protection materials and systems are contained in Ref. 17 and Figs. 71 through 74.

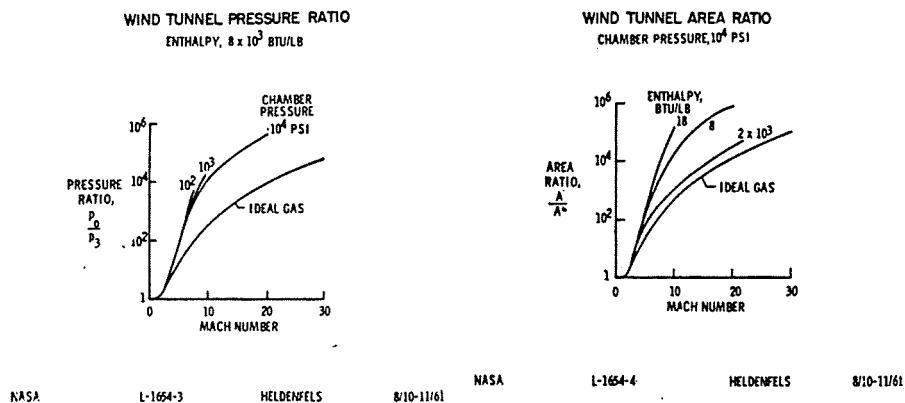


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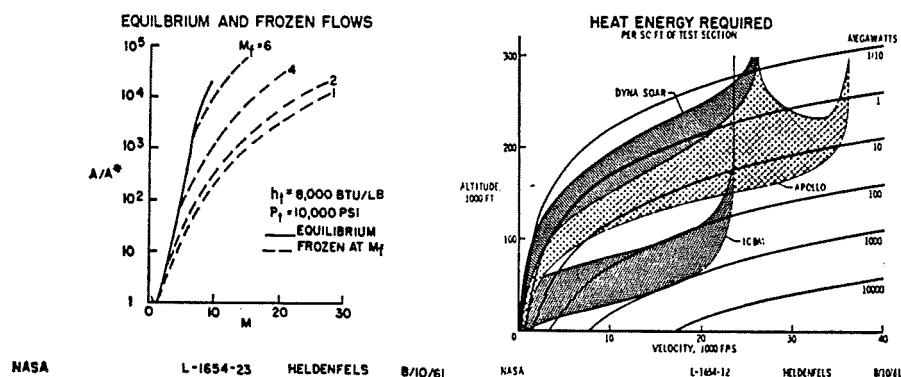
Fig. 58—10 MW Arc Tunnel—Enthalpy 8×10^3 Btu/lb, Area Ratio 10^4 , Test Section 20 in. diam.



(Left) Fig. 59—Thermodynamic Chart for Air.
(Right) Fig. 60—Wind Tunnel Velocity—Chamber Pressure, 10^4 psi.



(Left) Fig. 61—Wind Tunnel Pressure Ratio—Enthalpy, 8×10^3 Btu/lb.
(Right) Fig. 62—Wind Tunnel Area Ratio—Chamber Pressure, 10^4 psi.



(Left) Fig. 63—Equilibrium and Frozen Flows.
(Right) Fig. 64—Heat Energy Required—per sq. ft. of Test Section.

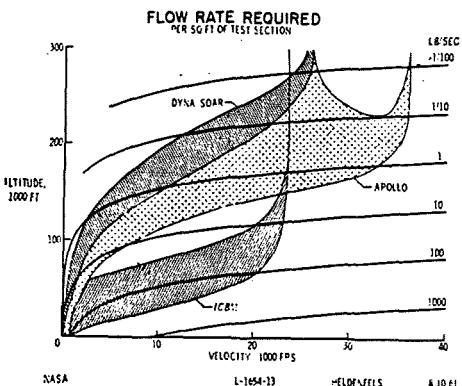
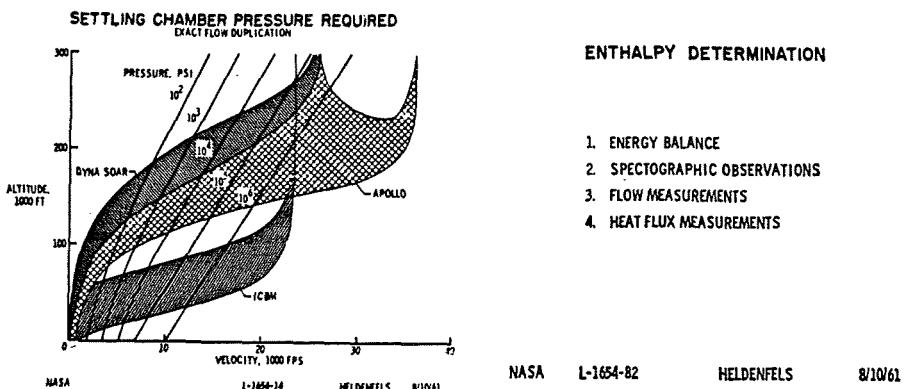
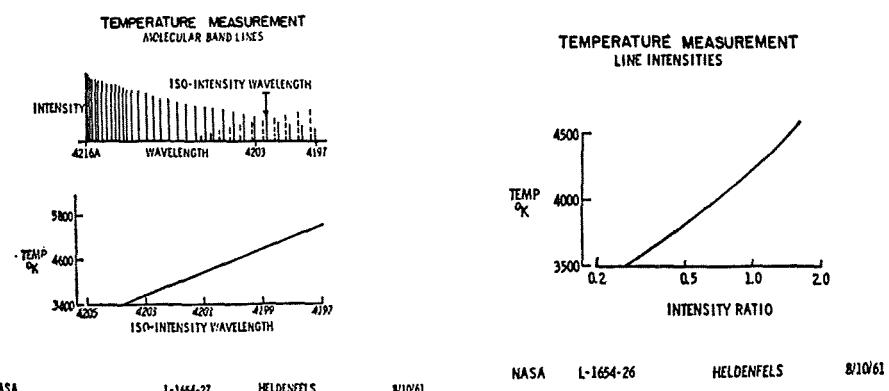


Fig. 65—Flow Rate Required—per sq. ft. of Test Section.



(Left) Fig. 66—Settling Chamber Pressure Required—Exact Flow Duplication.
(Right) Fig. 67—Enthalpy Determination.



(Left) Fig. 68—Temperature Measurement—Molecular Band Lines.
(Right) Fig. 69—Temperature Measurement—Line Intensities.

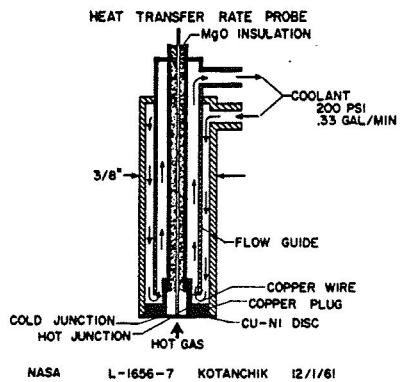


Fig. 70—Heat Transfer Rate Probe.

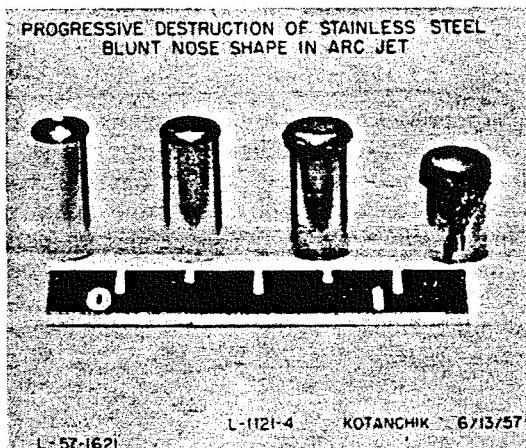
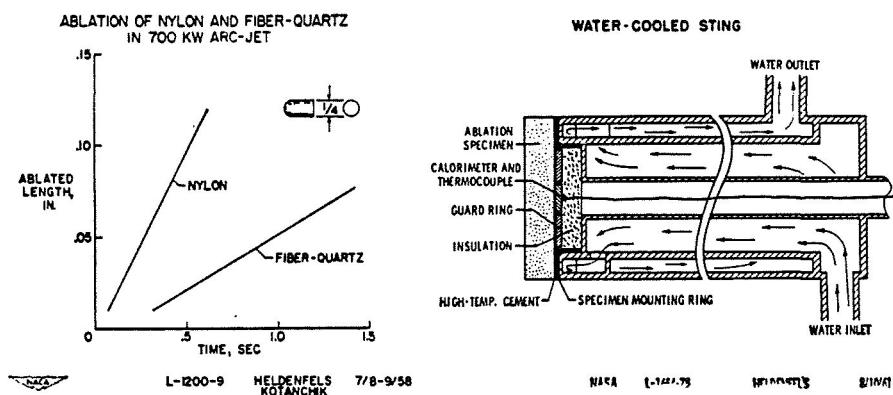


Fig. 71—Progressive Destruction of Stainless Steel Blunt Nose Shape in Arc Jet.



(Left) Fig. 72—Ablation of Nylon and Fiber-Quartz in 700 KW Arc-Jet.
(Right) Fig. 73—Water-Cooled Sting.

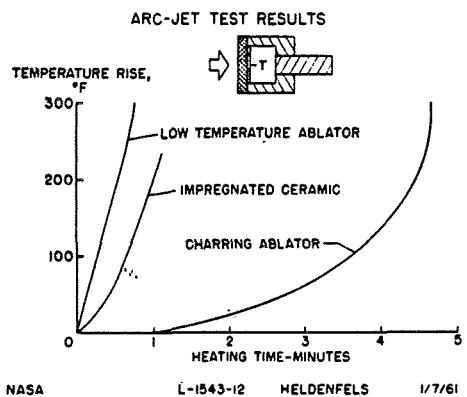
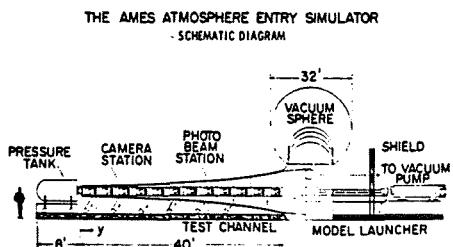


Fig. 74—Arc-Jet Test Results.

Re-entry Simulator

The aerodynamic devices previously discussed usually provide steady-heating conditions throughout a test, whereas actual re-entry involves a continuous variation of all parameters. A unique re-entry simulator has been developed at the Ames Research Center. Small test models are fired upstream into a hypersonic blowdown wind tunnel so that the model experiences the correct variation of flight velocity and atmospheric density during a test. The design of this facility is an excellent example of the use of similarity relations for simultaneously scaling aerodynamic heating, internal heat-transfer and thermal stress. (Ref. 18, Fig. 75)



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Fig. 75—The Ames Atmosphere Entry Simulator—Schematic Diagram.

COMBINED HEATING OF SUPERCIRCULAR RE-ENTRY

Re-entry at supercircular speed involves significant heat input by radiation from the hot gases surrounding the body. This radiant input must be pro-

duced in ground facilities along with the convective input. If aerodynamic facilities were capable of exact duplication of re-entry, this radiant component would be automatically provided. Because of the limitations of present ground facilities, thermal protection systems are tested by using a radiant source in conjunction with the convective heating of an arc-heated air-stream. Carbon-grid radiators have been used for this purpose at Langley; an arc-image furnace has been used at Ames. (Figs. 76-79)

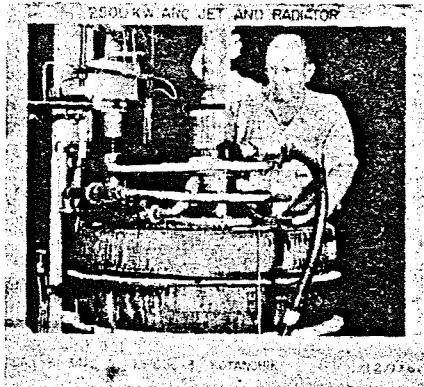


Fig. 76—2500 KW Arc Jet and Radiator.

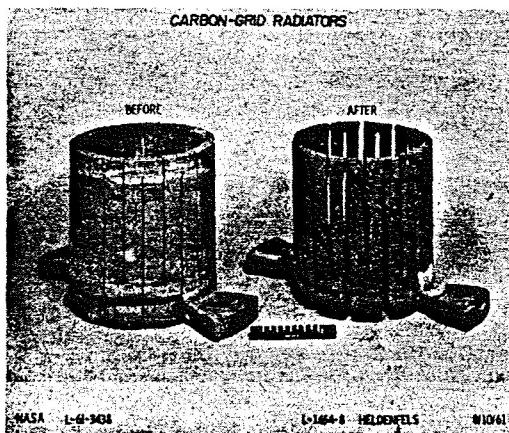
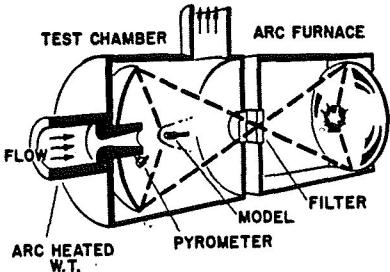


Fig. 77—Carbon-Grid Radiators.

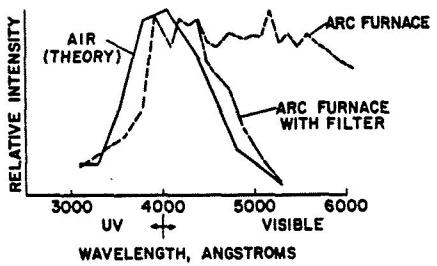
ENTRY HEATING SIMULATOR



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Fig. 78—Entry Heating Simulator.

SPECTRAL ENERGY DISTRIBUTIONS



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Fig. 79—Spectral Energy Distributions.

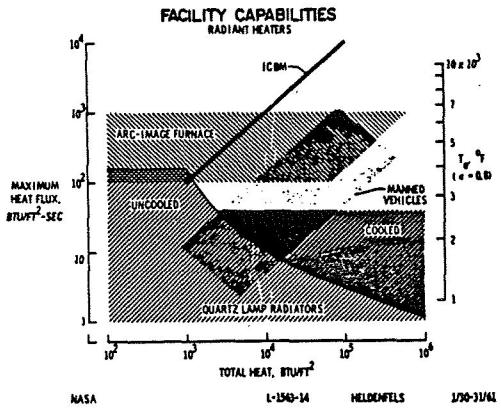


Fig. 80—Facility Capabilities—Radiant Heaters.

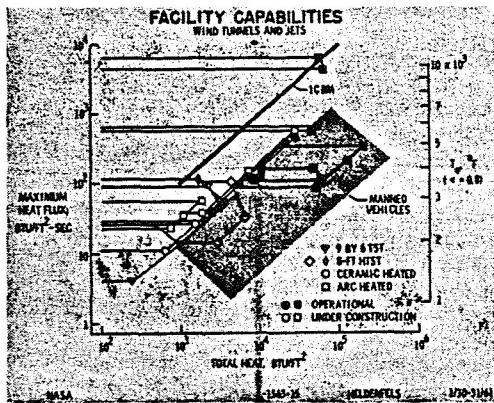


Fig. 81—Facility Capabilities—Wind Tunnels and Jets.

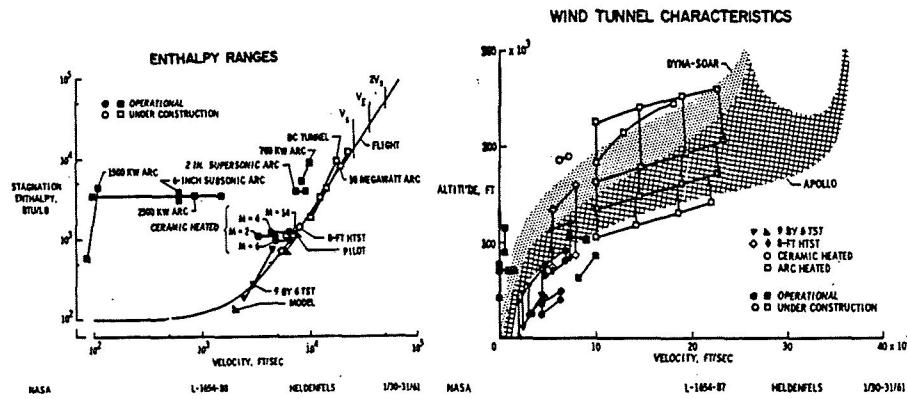


Fig. 82—Enthalpy Ranges.

Fig. 83—Wind Tunnel Characteristics.

SUMMARY OF FACILITY CAPABILITIES

The capability of many of the facilities previously discussed is compared, in Figs. 80 through 83, with the characteristics of the flight environment in terms of heating rate, heat load, altitude, velocity, and enthalpy to indicate the current gaps between facility technology and flight experience. A NASA motion picture (Film Serial L-657, 16 mm., silent, color) "High Temperature Testing of Aircraft Structures—1961" illustrates the research utilization of most of the test facilities described herein.

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